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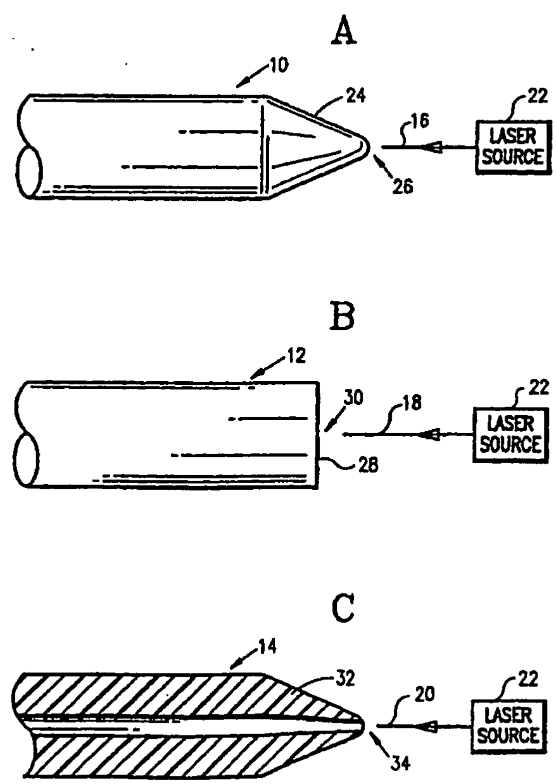
(54) Title: LENSED OPTICAL FIBERS & UNIQUE MICROPIPETTES WITH SUBWAVELENGTH APERTURES

(57) Abstract

A method for producing subwavelength near-field optical apertures includes directing a laser beam (16) at the top of a tapered optical fiber (10) to melt the fiber tip. The melting forms a lens at the tip, and the resulting structure is then coated with metal (42) in such a way that an aperture (44) is left open, or the aperture (44) is formed in the metal by means of an ion beam or a laser beam (16). In another embodiment, the tip of a micropipette (14) is melted by a laser beam (20) to form an aperture having thick walls.



LENSED OPTICAL FIBERS & UNIQUE MICROPIPETTES WITH SUBWAVELENGTH APERTURES

I Field of the Invention

The need for subwavelength apertures spans many area of science and technology from subwavelength optical imaging and nanofabrication with near field optics to electrical measurements of cellular biology with subwavelength apertures in micropipettes. The field of this invention is a method for making such a subwavelength aperture at the tip of an optical fiber that also behaves as a lens and for making micropipettes with apertures from as small as tens of nanometers with wall thicknesses as large as 1 mm.

II Background of the Invention

One reason for developing new methods to produce subwavelength apertures is that the field of near-field optics is one of the fastest growing areas of science and technology today. Previously, the most successful method for creating near-field optical apertures was the use of techniques to taper glass in order to provide is a subwavelength region at the tip of the tapered glass structure which could be coated with metal in order to produce a subwavelength aperture at the tip. [A. Harootunian, E. Betzig, M.S. Isaacson, and A. Lewis; Appl. Phys. Lett. 49,674 (1986); A. Lewis, M. Isaacson, E. Betzig, and A. Harootunian, United States Patent Number 4,917,462; Issued: April 17, 1990.]. These methods can be used to either produce a tapered micropipette or can be used to produce a tapered fiber optic element that can then be coated with metal to produce a subwavelength aperture. One aspect of these

methods that can be improved is the taper angle of the tip and the core to cladding ratio when an optical fiber is employed. This is necessary for high light transmissions since it is important that the light beam, as it progresses through such a tapered structure, traverses the smallest region of subwavelength dimensions while remaining as much as possible in the core of the fiber. There have been generally two procedures to improve this characteristic of near-field optical elements. One procedure has depended on etching of the fiber tip [Jiang S. Ohsawa, H. Yamada, K. Pangaribuan, T. Chtsu, M. Imai, K. and Ikai. A.; *Jpn. J. Appl. Phys.* 31,2282 (1992); S.J. Bukofsky and R.D. Grober. Appl. Phys. Lett. 71,2749 (1997)]. A second approach has to been to use an amended versions of the earlier pulling technology [Galina Fish, Sophin Kokotov, Edward Khachatryan, Andrey Ignatov, Rimma Glazer, Anatoly Komissar, Yuri Haifez, Alina Strinkovsky, Aaron Lewis and Klony Lieberman; Israel Patent Application Serial Number: 120181: Filed: February 9, 1997, PCT filed February 8, 1998]. Micropipettes have not been produced with small apertures and the thick walls that have been achieved in accordance with the present invention.

III State of Prior Art

In the past, there has been no approach to produce a lens with a subwavelength aperture at the tip in an optical fiber or to produce an aperture having a dimension in the region of tens of nanometers or around this region, either bigger or smaller, in a micropipette.

IV Summary of the Invention

The invention is a method to produce a subwavelength aperture in the tip of a tapered or untapered optical fiber in which the tip also behaves as a lens. The

method also allows the production of a micropipette with a small opening in its tip, with very thick walls surrounding the tip.

V Brief Description of the Drawings

The foregoing and additional object features and advantages will become apparent to those of skill in the art from the following detailed description of preferred embodiments, taken with the accompanying drawings, in which:

Figs. 1A, 1B and 1C are diagrammatic illustrations of the placement of a laser beam relative to glass structures for producing combined subwavelength apertures with lenses in accordance with the present invention;

Figs. 2A and 2B are diagrammatic illustrations of an optical fiber (in partial cross-section) and a micropipette respectively, after treatment by a laser, in accordance with the invention; and

Fig. 3 is a diagrammatic illustration of a cantilevered glass structure incorporating the invention.

VI Description of the Invention

The invention is a device in which there is both a lens and a subwavelength (tens of nanometers or selected dimensions around these dimensions) aperture at the tip of an optical fiber or a small hole that could be tens of nanometers or more or less than these dimensions in a glass capillary with thick walls surrounding this hole, and a method for fabricating such devices. In order to accomplish this in one embodiment a glass structure 10, which may be an optical fiber tapered by standard Harootunian and Lewis methodology or by etching, as illustrated in Figure 1A, or a fiber structure 12 in Fig. 1B, formed with tapering or etching, or in another embodiment a similar

combination for a micropipette 14 (Fig. 1C) is placed in front of a laser beam 16 (Figure 1A), laser beam 18 (Fig. 1B), or laser beam 20 (Fig. 1C) produced by a carbon dioxide laser 22, or some other appropriate laser beam. The laser beam and the corresponding glass structure are aligned on one axis with, for example, the tip 24 of the tapered structure 10 in the focus 26 of the laser beam 16. Similarly, beam 18 is aligned with the end 28 of structure 12 at focus 30 and beam 20 is aligned with the tip 32 of structure 14 at focus 34. Then the laser beam is turned on for a few seconds in order to melt the tip 24 into a lens 36 if it is an optical fiber 10 or 12 (Figure 2A) and into a structure that has a small opening 38 with large (thick) walls 40 if it is a micropipette 14 (Figure 2B). The resulting optical fiber device 10 (or 12) is then coated with metal 42 such that an aperture 44 is left opened at the tip. Alternatively, the device 10 is completely coated and then a focused ion beam or a laser such as the femtosecond laser 22 is used to make the aperture. In the case of the micropipette 14 (Figure 2B) the device can be left uncoated.

With both micropipettes or optical fibers, asperities can be grown on the tip either electrochemically or with such techniques as ion or electron beams to produce a fine tip on the end of structures 10, 12 or 14 for atomic force microscopy. In addition, the laser beam could also be used to heat the optical fiber or the micropipette to form a curved cantilevered device 50 (Fig. 3), having a tip 52 incorporating a lens such as lens 36 (Fig. 2A), as has been accomplished previously (K. Lieberman and A. Lewis, "Bent Probe Microscopy", United States Patent Number: 5,677,978; Issued: October 14, 1997). The laser beam can also be used to put a flat surface 54 on the curved cantilever to provide a good reflecting surface for atomic

force microscopy, although these are simply additions that this invention could also work with. In other words these alterations in the structure are compatible with this invention but the invention can be employed with or without them.

VII Advantages over Prior Art

The above-described structures can act both as lenses and subwavelength apertures and can also behave in a hybrid fashion that has never been seen before. Specifically, it has been observed that as the distance is increased between a surface and the tip of the aperture there can be, in fact, an increase in the resolution or at the very least a maintaining of the resolution as was maintained in the near-field. This allows high resolution even with a separation between the subwavelength aperture and the object that is being imaged and this has never been seen before. In addition, in terms of near-field optics the transmission efficiency of such apertures, which is a very important characteristic is seen to increase and transmissions out of the subwavelength tip have been measured with only two orders of intensity decrease in the intensity that was injected into the fiber. Furthermore, these micropipettes would be very useful for aperturing high intensity x-ray sources.

VIII Applications

There are many areas of applications for such devices that increase the distance of high resolution that is only normally seen in the near-field. One area is in the field of information storage where resolutions below the surface can now be as high as has previously been seen only on the surface. In addition, in the area of microchip inspection where there is a technique of chemical mechanical polishing of the microchip where important features are below the surface and such tips could be

useful in imaging such features. In addition, in any area of near-field optics which requires higher throughput of radiation this is an important invention. Finally, micropipettes with such structures would be very good, for example, to hold cells while measuring the electrical properties of the cells.

What is Claimed is:

1. A method to produce a hybrid structure of an aperture that is either tens of nanometers or smaller or larger than these values on a lens that is placed at the end of tapered or untapered optical fiber or micropipette by using a laser beam appropriately placed in opposition to the tip of the optical fiber or the micropipette to melt the tip of these structures to produce an effective lens which can be coated to produce an aperture at the tip of an optical fiber by the coating procedure or by high energy beams that can remove metal or to use the method to produce a micropipette with a small opening of tens of nanometers or smaller or larger than these values in a thick surrounding wall and this structure could be coated or could remain uncoated.

2. A method as in claim 1 in which the structure is cantilevered for simultaneous force sensing.

3. A method as in claim 1 in which the structure has an asperity grown at the tip to produce a high resolution point for such applications as force sensing or tunneling.

4. A method as in claim 2 in which the structure has an asperity grown at the tip to produce a high resolution point for such applications as force sensing or tunneling.

5. A method as in claim 2 in which a small mirror is imposed on the cantilever for good reflection in force sensing.

6. A method as in claim 4 in which a small mirror is imposed on the cantilever for good reflection in force sensing.

7. A device which is a hybrid structure of an aperture that is either tens of nanometers or smaller or larger than these values on a lens that is placed at the end of tapered or untapered optical fiber or micropipette by using a laser beam

appropriately placed in opposition to the tip of the optical fiber or the micropipette to melt the tip of these structures to produce an effective lens which can be coated to produce an aperture at the tip of an optical fiber by a metallic coating procedure or by high energy beams that can remove metal or to produce a device of a micropipette with a small opening of tens of nanometers or smaller or larger than these values in a thick surrounding wall and this structure could be coated or could remain uncoated.

8. A device as in claim 7 in which the structure is cantilevered for simultaneous force sensing.

9. A device as in claim 7 in which the structure has an asperity grown at the tip to produce a high resolution point for such applications as force sensing or tunneling.

10. A device as in claim 8 in which the structure has an asperity grown at the tip to produce a high resolution point for such applications as force sensing or tunneling.

11. A device as in claim 8 in which a small mirror is imposed on the cantilever for good reflection in force sensing.

12. A device as in claim 10 in which a small mirror is imposed on the cantilever for good reflection in force sensing.

FIG. 1A

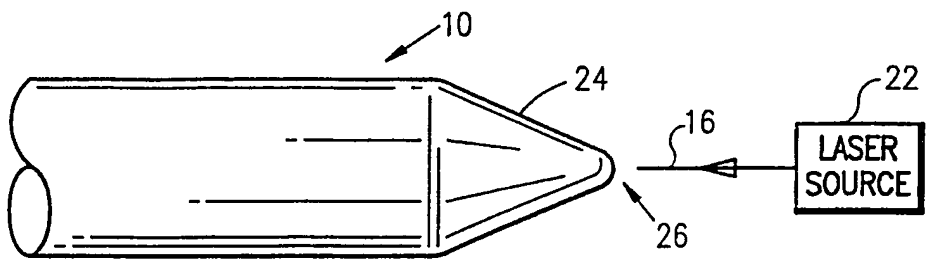


FIG. 1B

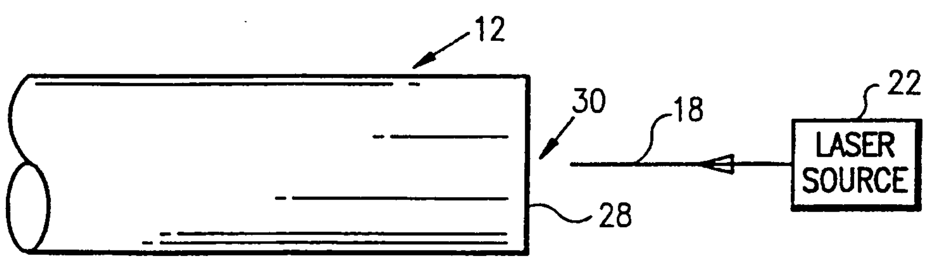


FIG. 1C

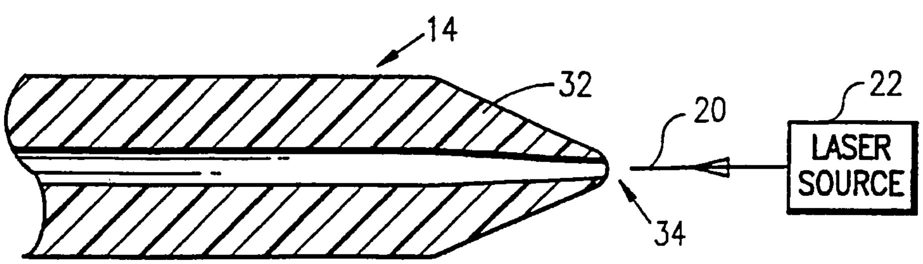


FIG. 2A

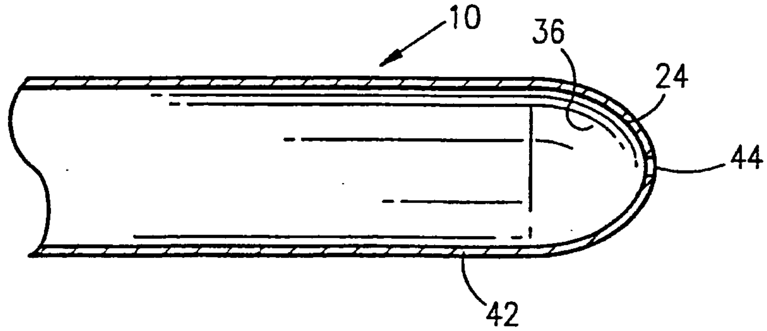


FIG. 2B

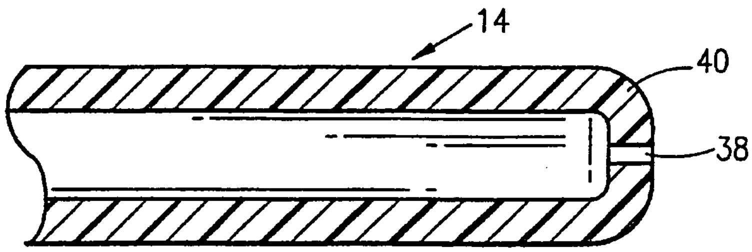
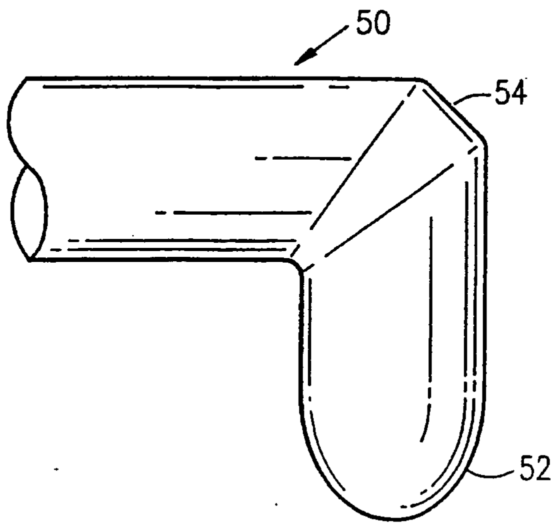


FIG. 3



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/27913

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : GO2B 6/02; C03B 37/00
US CL : 385/147; 65/387

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/147, 12, 13, 43, 125; 65/387

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST (fiber optic, micropipette, subwavelength aperture, microlens, laser, melt, fiber tip, pipette, near field optical microscopy)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,917,462 A (LEWIS et al) 17 April 1990 (17/04/90), see entire document.	1-12
Y	US, 5,677,978 A (LEWIS ET AL) 14 October 1997 (14/10/97), see entire document.	1-12
Y	US, 4,932,989 A (PRESBY) 12 June 1990 (12/06/90), see abstract.	1-12
A	US 5,361,314 A (KOPELMAN ET AL) 01 November 1994 (01/11/94), see entire document.	1-12
A	US 5,485,536 A (ISLAM) 16 January 1996 (16/01/96), see entire document	1-12

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
03 FEBRUARY 2000	16 FEB 2000

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